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Effects of Dietary Fiber on Glucose Tolerance of Normal Men

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SUMMARY

26 g of dietary fiber sources—hard red spring wheat bran (HRS), soft white wheat (SWW), corn bran (CB), soy hulls (SH), freeze-dried apple powder (AP), and freeze-dried carrot powder (CP)—was fed to 15 men as part of a mixed diet. Oral glucose tolerance and one hour postprandial serum glucose were measured after one month of each fiber source and were compared with findings measured after one month of the diet without added fiber. The subjects' energy intakes and expenditures were nearly constant throughout the study. The fiber sources contained 50.8% (HRS), 44.1% (SWW), 92.1% (CB), 86.7% (SH), 25.6% (AP), and 31.0% (CP) fiber. Oral glucose tolerance improved significantly when subjects ate CB, SH, AP, and CP. Corrected insulin response at the glucose peak (CIRp) and peripheral insulin sensitivity (GTp) improved when subjects were fed CB, SH, AP, and CP. Fasting plasma glucagon and plasma glucagon responses to oral glucose were significantly lower after feeding AP or CP. Hard spring wheat bran was associated with higher fasting plasma glucagon and a similar plasma glucagon response to oral glucose compared with those of controls. Postprandial serum glucose concentrations were significantly lower when subjects were fed fiber-supplemented (CB and SH) diets than when they were fed the same diet without fiber. Effects of the dietary fiber sources on carbohydrate metabolism seemed dependent on the composition of the source. Improved oral glucose tolerance was associated with improved insulin release and peripheral insulin sensitivity and decreased plasma glucagon concentrations. DIABETES 28:496–502, May 1979.

Effects of the diet's composition on plasma glucose, insulin, and glucagon have received considerable attention in recent years.[1–11] It is known, for example, that high-carbohydrate, low-fat diets improve the oral glucose tolerance of normal[1–3] and obese[4] subjects and patients with mild diabetes mellitus.[5–7] The improvement was associated with lower plasma insulin concentrations.[5–7] Carbohydrate restriction, on the other hand, is reported to decrease insulin and increase glucagon levels[8] and impair glucose tolerance.[2] Similarly, it was shown that high-fat diets worsen carbohydrate tolerance.[9] Since high-carbohydrate diets induce and aggravate fasting hypertriglyceridemia,[10–13] these diets are not widely used in the management of patients with diabetes mellitus.

The incidence of diabetes mellitus is low in ethnic groups such as Yemenite Jews, South African Bantu, and New Zealand Maori who consume large quantities of dietary fiber. However, the incidence of diabetes is higher in members of such groups who have adopted Western patterns of living and, thus, decreased their consumption of polysaccharides and dietary fiber.[14,15] The hypothesis that the beneficial effect of complex carbohydrates is due to the smaller increase in blood sugar levels that occurs after their ingestion than after ingestion of equivalent amounts of refined carbohydrates[16] has recently been confirmed by Jenkins et al.[17,18] They found lower postprandial glucose and insulin responses in healthy volunteers when guar flour, pectin, or both were added to the carbohydrate load. Their findings suggest that the presence of unabsorbable carbohydrates in a meal may limit the rise of blood glucose and insulin that follows a meal containing carbohydrates. Kiehm et al.[19] found fasting plasma glucose values to be significantly lower in 10 diabetic patients after 2 wk on a high-carbohydrate, high-fiber diet, and Brodribb and Humphreys[20] found a fall in the glucose tolerance curves of 40 patients with diverticular disease who were treated as outpatients with wheat bran, 24 g per day for 8 months. These studies suggested that dietary fiber may not only decrease the absorption of carbohydrates but may also have a systemic effect, perhaps by enhancing the peripheral insulin sensitivity. Since high-carbohydrate diets alone improve glucose

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tolerance and peripheral insulin sensitivity,[5,17] we studied the effects of various sources of dietary fiber on oral glucose tolerance in normal male subjects fed otherwise constant diets, who were closely supervised in a metabolic unit.

MATERIAL AND METHODS

EXPERIMENTAL DESIGN AND DIETS

Fifteen male volunteers, ages 19–54, were admitted to the Metabolic Unit of the Human Nutrition Laboratory, SEA, U.S. Department of Agriculture, after they gave informed consent (according to the Declaration of Helsinki) and after medical, psychologic, and nutritional evaluations were made to establish their normality. The subjects lived in the Metabolic Unit for periods of 4–8 months under close supervision. Each subject was fed a constant diet, prepared from conventional foods and designed to meet his individual nutrient needs according to the guidelines of the National Research Council.[21] The low-fiber, basal diet contained 16% of calories as protein (70% animal), 40% as fat (linoleate:saturated fat ratio = 0.3), and 44% as carbohydrate (9 ± 2% of total calories as sucrose). The calculated dietary cholesterol ranged from 360 to 780 mg per day, depending on the calorie level required for each subject. The calculated crude fiber content was 1 g/1000 kcal. The menus were prepared in a six-day cycle. An example of a menu is given in Table 1.

To maintain a constant level of fitness, the previous level of physical activity of each subject was estimated by history and then an exercise prescription on a treadmill was given according to the guidelines of Cooper.[22] Each subject's previous caloric intake was estimated by history and was subsequently adjusted during the initial period of equilibration so that his weight remained constant. Two subjects were obese (percentage of desirable body weight, 166 and 149%). The other 13 subjects had a mean percentage of desirable body weight of 104.7%, with a range from 91 to 120. The general status, vital signs, and body composition (by measurement of the midupper arm's circumference and the biceps, triceps, subscapular, and supra-iliac skin folds) were assessed daily.

After an initial equilibration period of 30 days on the control, low-fiber diet (except for two subjects, who were first fed a fiber-supplemented diet and then the basal diet), the subjects were fed 26 g of one of the fiber sources—hard red spring wheat (HRS), soft white wheat bran (SWW), corn bran (CB), soybean hulls (SH), freeze-dried apple powder (AP), or freeze-dried carrot powder (CP)—daily in 180 g of bread for 30 days. Another source of dietary fiber was fed during subsequent experimental periods, except in four subjects who were fed the basal diet a second time that was halfway through their time in the unit, i.e. after two to three periods of fiber-supplemented diet. Each subject was fed at least two different sources of fiber; three subjects were fed the same source of dietary fiber (HRS, SWW, or SH) during two different balance periods 2–3 months apart. Duplicate diets were collected for 12 days for chemical analysis and estimation of the energy value by bomb calorimetry.

TABLE 1
Three typical daily menus

Menu		Grams of food A	B	C
Breakfast	Grape juice	80	150	150
	Scrambled eggs	60	90	90
	Bread	20	40	40
	Margarine	15	15	15
	Jelly	20	20	20
	Milk	208	208	208
	Tea/coffee	205	205	205
Noon meal	Baked chicken breast	60	70	70
	Mashed potatoes	130	265	265
	Bread	70	60	60
	Butter	5	15	25
	Cheese	25	25	25
	Peach pie	140	140	140
	Sugar cookies	0	0	10
	Tea/coffee	205	205	205
Evening meal	Orange juice	120	120	120
	Spaghetti with meat sauce	340	340	340
	Bread	50	40	70
	Butter	10	10	15
	Cheese	0	0	25
	Cherries	100	100	100
	Sugar cookies	20	20	30
	Tea/coffee	205	205	205
Evening snack	Pineapple-orange juice	200	200	200
	Sliced beef sandwich	90	90	90
Kilocalories		2700	3000	3500

TABLE 2
Composition of the high-fiber and low-fiber test meals

	Total (g)	Total (kcal)	Protein (g)	Fat (g)	Carbohydrates (g)	Crude fiber (g)	Total fiber (g)
Raspberry Kool-aid drink	275.8	100	0	0	24.89	0	0
Bread:							
low fiber	180	486	15.66	5.76	90.90	0.36	4.89
high fiber	180	486	15.66	5.76	90.90	6.3	27.67
Margarine	10	72.4	0.06	8.04	0.09	0	0
Jelly	50	127.5	0	0	32.25	0	0
Tea	1	2.85	0	0	0.71	0	0
Total							
(g)	516.8		15.72	13.8	148.82	—	—
(kcal)		788.75	62.88	124.2	595.28	—	—
Percent of total calories			8.0	15.8	75.76	—	—

TABLE 3
Mean (±SE) serum glucose responses (mg/dl) during oral glucose tolerance tests

Diet		0 min	30 min	60 min	120 min	180 min
Basal	(N = 8)	76.2 ± 2.0	145.0 ± 6.9	113.0 ± 6.3	80.4 ± 6.0	65.2 ± 4.9
HRS	(N = 8)	75.6 ± 2.8	131.0 ± 11.6	110.6 ± 9.5	75.5 ± 7.4	61.0 ± 5.6
P		NS	NS	NS	NS	NS
Basal	(N = 5)	75.4 ± 3.4	144.6 ± 8.5	110.2 ± 7.5	86.5 ± 10.5	75.3 ± 9.5
SWW	(N = 5)	75.6 ± 5.0	137.7 ± 6.0	124.7 ± 2.6	96.5 ± 12.0	75.8 ± 8.0
P		NS	NS	NS	NS	NS
Basal	(N = 5)	81.3 ± 1.0	133.6 ± 5.3	109.2 ± 9.1	64.5 ± 7.1	81.2 ± 4.3
CB	(N = 5)	80.9 ± 1.2	122.2 ± 1.8	70.6 ± 6.4	71.8 ± 12.0	60.7 ± 7.6
P		NS	NS	<0.05	NS	NS
Basal	(N = 7)	80.5 ± 1.0	130.1 ± 4.3	113.4 ± 6.6	67.2 ± 5.5	73.5 ± 5.6
SH	(N = 7)	78.6 ± 1.6	104.2 ± 6.4	78.1 ± 6.0	73.7 ± 2.5	65.2 ± 6.4
P		NS	<0.05	<0.05	NS	NS
Basal	(N = 8)	79.8 ± 1.4	140.3 ± 7.0	109.8 ± 8.4	73.5 ± 6.7	68.9 ± 2.5
AP & CP	(N = 8)	75.1 ± 1.4	115.8 ± 8.1	95.9 ± 8.8	75.5 ± 7.4	69.6 ± 4.2
P		<0.05	<0.05	<0.05	NS	NS
Basal*	(N = 2)	112.2 ± 0.6	193.9 ± 5.5	247.9 ± 4.2	215.2 ± 10.0	81.6 ± 12.0
CB*	(N = 2)	101.7 ± 9.2	193.3 ± 5.0	221.2 ± 5.4	129.2 ± 43.0	83.9 ± 15.0
Basal I	(N = 4)	77.4 ± 2.4	151.9 ± 16.5	114.5 ± 9.0	82.5 ± 9.0	61.2 ± 7.5
Basal II	(N = 4)	83.1 ± 2.9	154.1 ± 12.0	127.4 ± 14.0	84.6 ± 3.8	61.6 ± 10.0
P		NS	NS	NS	NS	NS

* Two subjects had abnormal oral glucose tolerance.

At the end of each 30-day period and after 12 hours of fasting, the volunteers were given an oral load of 75 g of glucose in 325 ml of water (Trutol, Sherwood Medical Industries)* in 4–5 min. Venous samples were obtained through a heparinized indwelling Teflon catheter at 0, 30, 60, 120, and 180 min in some volunteers and every 15 min for 3 h in others, for glucose, insulin, and glucagon determinations.

In six volunteers, 1 h postprandial serum glucose was measured subsequent to feeding low- and high-fiber test meals (Table 2). All six subjects were fed the low-fiber test meal at the end of a 30-day control (low-fiber) period. Subsequently they were fed high-fiber meals. Three subjects were fed a meal containing 26 g of CB and the other three subjects a meal containing 26 g of SH. At the end of each study period, the subjects were fed a high-fiber test meal in 15 min, and a blood sample for serum glucose determination was taken 1 h later.

CHEMICAL ANALYSIS

Serum glucose was determined using a glucose oxidase–peroxidase method,[23] serum insulin by a modification of the double antibody technique,[24] and plasma glucagon by the method of Kuku et al.[25] The various sources of dietary fiber were analyzed for hemicellulose; cellulose, lignin, protein, ash, and total neutral detergent fiber contents by standard methods.[26–31] The results will be published in detail elsewhere.

* Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable.

STATISTICAL ANALYSIS

Data were analyzed by computer by use of one-way analysis and by paired *t* test utilizing Dunnett's correction for multiple comparisons with a control.[32] The results are given as means ± standard errors.

Following the mathematical approach of Sluiter et al. to evaluate the pancreatic function (insulin release) independently of the glucose level reached, we calculated the corrected insulin response at the glucose peak (CIRp) using the formula[33]

$$CIRp = \frac{Ip\ 100}{Gp(Gp - 70)},$$

in which Ip is the insulin peak (in microunits per milliliter) and Gp the glucose peak (in milligrams per 100 ml).

Since it is known that the insulin:glucose ratio could be spuriously influenced by intestinal absorption abnormalities and glucose loss in the urine,[34] a parameter of glucose tolerance (GTp) was calculated according to the following formula, which is an index of peripheral insulin sensitivity:[34]

$$GTp = \frac{10^6}{Gp^2(Gp - 70)}$$

CIRp and GTp were calculated using the insulin and glucose values at the glucose peak.

RESULTS

DIET

The diet was well accepted by the subjects, and they experienced no untoward effects. One-way analysis of variance of the data on the composition of the duplicate diets

showed that the addition of fiber to the diet did not significantly modify its composition of major nutrients.

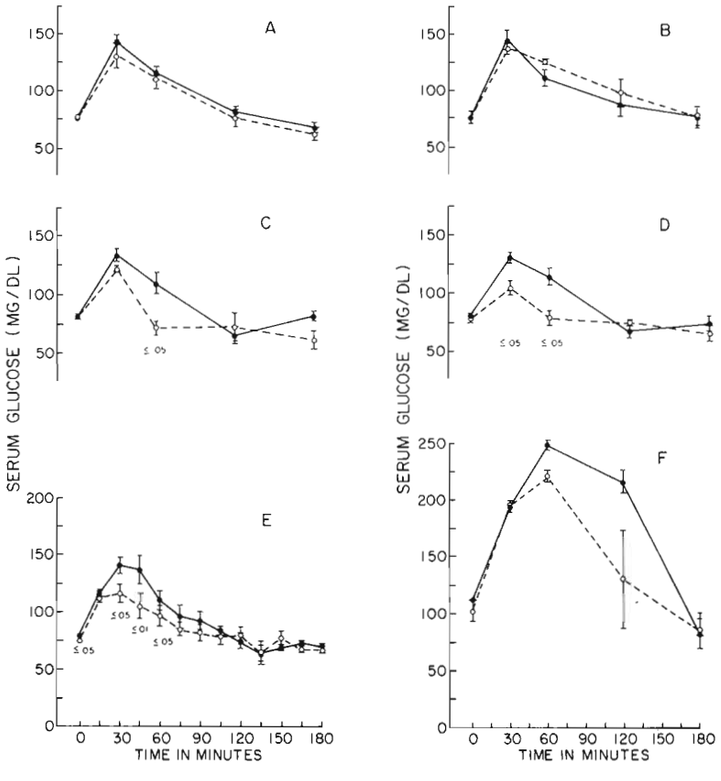
HRS and SWW contained less than 50% dietary fiber and were grossly similar in composition (35% hemicellulose, 9% cellulose, and 3% lignin). CB contained more than 92.1% dietary fiber, of which 70% was hemicellulose, 22% was cellulose, and 0.1% was lignin; SH contained 33% hemicellulose, 53% cellulose, and 0.76% lignin, or, 86.8% dietary fiber. The freeze-dried apple and carrot powders contained 8.6 and 12%, respectively, of neutral detergent fiber. These sources are also known to be rich in pectin (17 and 19%, respectively),[35] which gives a total fiber content of 25.6 and 31%, respectively.

No significant changes were observed in body weight or body composition of the subjects. The mean coefficient of variation for body weight was 0.76%, and the coefficient of variation for the skinfold measurements averaged 0.098%. Some of the volunteers experienced slight, but not statistically significant, increments in percent of fat (average, 0.85%).

GLUCOSE, INSULIN, AND GLUCAGON RESPONSES

The serum glucose responses to the oral glucose load during the basal and the different fiber diets are presented in Table 3 and Figure 1. In subjects fed HRS (Figure 1A) and SWW (Figure 1B), the mean serum glucose responses to oral glucose loads were not significantly different from the responses when the subjects were fed the basal diet. The glucose response curves for subjects fed CB, SH, CP, and AP were generally flatter than the curves for the same subjects when they were fed the basal diet; some of the differences were statistically significant (Figure 1C to 1E).

FIGURE 1. Mean (±SE) serum glucose responses in male subjects given 75 g glucose orally after 30 days on a low-fiber basal diet (solid circles) and after 30 days on the basal diet supplemented with 26 g per day of a source of dietary fiber (open circles). (A) Hard red spring wheat bran (N = 8). (B) Soft white winter wheat bran (N = 4). (C) Corn bran (N = 5). (D) Soybean hulls (N = 7). (E) Freeze-dried apple powder (N = 4) and carrot powder (N = 4). (F) Corn bran (N = 2, subjects had mild, fasting hyperglycemia and abnormal glucose tolerance).



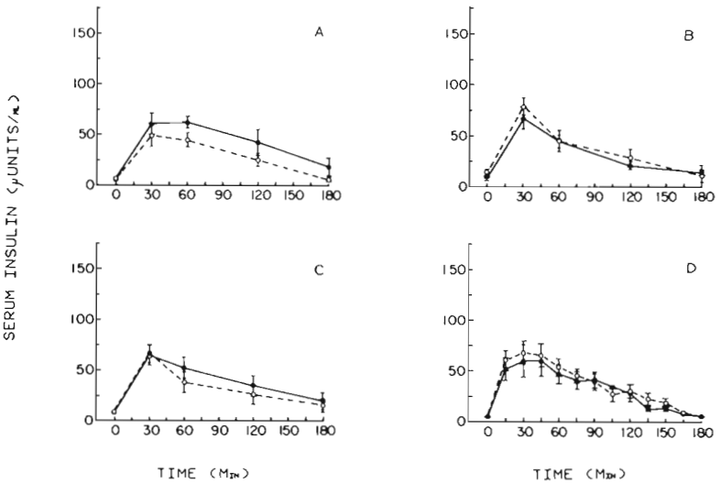


FIGURE 2. Serum insulin responses in healthy male subjects given 75 g glucose orally after 30 days on a low-fiber basal diet (solid circles) and after 30 days on the basal diet supplemented with 26 g a day of a source of dietary fiber (open circles). (A) Hard red spring wheat bran (N = 6). (B) Corn bran (N = 5). (C) Soybean hulls (N = 6). (D) Freeze-dried apple powder (N = 4) and carrot powder (N = 4).

Two subjects had mild fasting hyperglycemia and abnormal glucose tolerance: their mean serum glucose concentration at 120 min after ingestion of 75 g glucose was 215.2 ± 9.9 mg/dl, when they were fed the basal diet. After 30 days on the basal diet supplemented with CB, their glucose tolerance improved (mean serum glucose concentration at 120 min after ingestion of 75 g glucose was 129.2 ± 43 mg/dl) (Figure 1F, Table 3). When one of these hyperglycemic subjects was fed SWW twice, 60 days apart, his glucose tolerance curves reached higher peaks than when he was fed the basal diet.

Three subjects fed the same source of dietary fiber (SWW, SH, or HRS) twice, separated by 30 days on the basal diet and 30 days on the basal diet supplemented with a different fiber source, displayed similar glucose tolerance curves for both periods of same-fiber supplementation. Four subjects fed the basal diet twice, separated by 90 or 120 days of fiber-supplemented diets, showed similar mean glucose tolerance curves after each period of the basal diet (Table 3).

The insulin response curves after the basal and fiber-supplemented basal diets were not significantly different in any of the subjects fed any of the fibers (Figure 2), except one obese (135.5 kg) subject who had elevated fasting insulin concentrations and abnormal glucose tolerance (Figure 3). He displayed a decreased insulin response to oral glucose after 30 days of CB supplementation. Improvements of his glucose tolerance and insulin response were not associated with weight loss or changes in skinfold thicknesses. Samples for insulin determination were not available from the other mildly hyperglycemic subject or the subjects fed SWW.

The mean oral glucagon response curve in subjects who had improved glucose tolerance after being fed a fiber-supplemented basal diet was somewhat lower after 30 days on the fiber diet than on the basal diet, and some of the differences were significant in subjects fed apple or carrot powder (Figure 4A). Three of the subjects fed HRS, who had similar glucose tolerance curves after being fed the

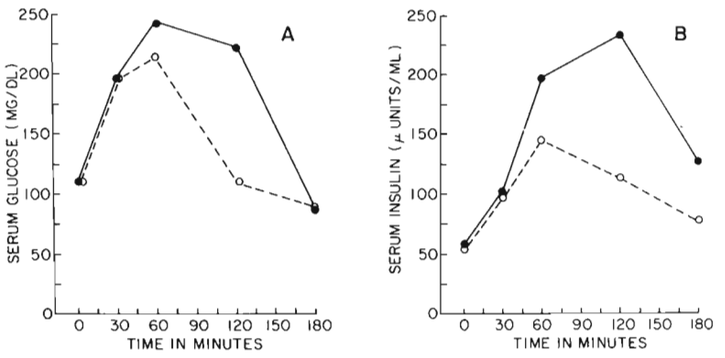


FIGURE 3. Serum glucose (A) and insulin (B) responses in an obese subject with mild hyperglycemia given 75 g glucose orally after 30 days on the basal diet (solid circles) and after 30 days on the basal diet supplemented with 26 g corn bran a day (open circles).

basal and fiber-supplemented diets, displayed fasting glucagon values that were generally higher than their control values and their responses to oral glucose were similar to their control values (Figure 4B).

PANCREATIC FUNCTION AND INSULIN ACTIVITY

The insulin response at the glucose peak (CIRp) improved from 0.55 ± 0.04 to 1.12 ± 0.13 ($P \leq 0.06$) with CB, from 0.62 ± 0.14 to 1.00 ± 0.11 ($P \leq 0.05$) with AP and CP, and from 0.72 ± 0.11 to 1.75 ± 0.49 (statistically not significant) with SH; with HRS, the CIRp did not change at all. Similarly, the insulin activity (GTp) increased from 0.87 ± 0.1 to 1.17 ± 0.03 with CB, from 1.0 ± 0.07 to 2.5 ± 0.06 with SH, and from 0.83 ± 0.16 to 1.48 ± 0.22 ($P \leq 0.01$) with AP and CP.

POSTPRANDIAL SERUM GLUCOSE

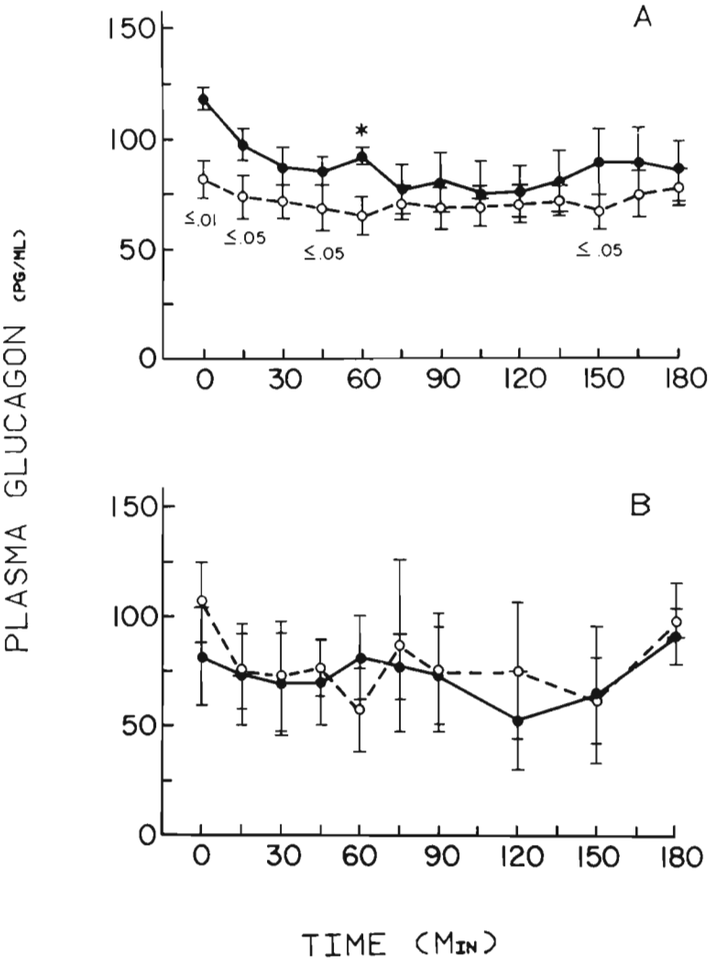
The mean serum glucose (±SE) 1 h after the low-fiber test meal (six subjects) was 143.6 ± 29 mg/dl, whereas after the high-fiber test meals (three subjects fed CB and three fed SH) was 102.2 ± 18 mg/dl ($P \leq 0.0057$).

DISCUSSION

We studied the effects of six different sources of dietary fiber on the glucose, insulin, and glucagon responses of human volunteers to oral glucose. The results show that the glucose tolerance curves were higher when volunteers were fed the low-fiber, basal diet than when 26 g of CB, SH, AP, or CP were added to the diet. The two wheat brans (HRS and SWW) did not improve glucose tolerance. This suggests that the effects of dietary fiber may be related to the composition of fiber in the dietary source. Although the two wheat brans were grossly similar in composition, they differed markedly in composition from the other dietary fiber sources studied. The improvement of the glucose tolerance test with AP and CP, which contained less dietary fiber than the wheat brans, also supports the concept that the metabolic effects of dietary fiber may be related to its composition rather than to the amount consumed. Our study, however, does not provide an explanation for the difference in effects of fiber sources, which was also observed by others.[36]

Our findings also suggest that dietary fiber not only reduces the rise of blood sugar (possibly due to slowed or decreased intestinal absorption, as suggested by Jenkins et al.[17,18]) but may improve insulin release and/or peripheral insulin activity. Although no significant differences in the insulin responses to oral glucose were observed before and after consumption of any of the fiber sources for one month (Figure 2), except in one obese subject (Figure 3), the CIRp, (the insulin:glucose ratio independent of the glucose level), considered to be a good indicator of beta cell response to oral glucose,[33] improved with CB, SH, AP, and CP. However, the difference was significant only with AP and CP ($P \leq 0.05$). The glucose tolerance factor calculated at the glucose peak (GTp) also improved after feeding SH or AP and CP ($P \leq 0.01$), suggesting that dietary fiber somehow improved the peripheral insulin activity. The fasting plasma glucagon level and glucagon responses to an oral glucose load were significantly lower after subjects were fed the diet with AP or CP than after they were fed the basal diet (Figure 4A). The better utilization and clearance of the oral glucose load observed when the volunteers were fed AP and CP might be due to the lower glucagon levels. The feeding of HRS, which did not improve the oral glucose tolerance, was associated with higher fasting glucagon levels and with glucagon responses to oral glucose similar to those seen after feeding the basal diet (Figure 4B). The mechanism by which some sources of dietary fiber increase insulin release and/or insulin activity and decrease glucagon release is not clear from our study. Possibly, some

FIGURE 4. Mean (±SE) serum glucagon responses in subjects given 75 g glucose orally after 30 days on a basal diet (solid circles) and after 30 days on a fiber-supplemented basal diet (open circles). (A) Freeze-dried apple powder (N = 4) and carrot powder (N = 4). *N = 6. (B) Hard red spring wheat bran (N = 3).



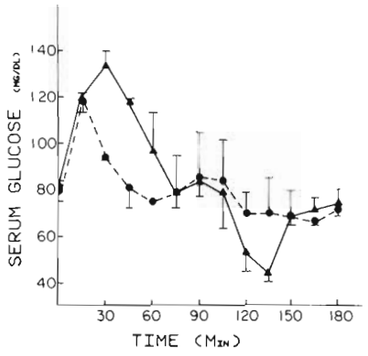


FIGURE 5. Mean (±SE) serum glucose responses in two subjects given 75 g glucose orally after 30 days on the basal diet (triangles) and after 30 days on the basal diet supplemented with 26 g of soybean hulls daily (circles).

sources of dietary fiber may affect the release of gastrointestinal hormones, which in turn affect insulin and glucagon secretion. Clearly, further studies are necessary to delineate the mechanism for these findings.

Variability of the plasma glucose response of individuals to repeated identical oral glucose tolerance tests performed 48 h[37] or 1 wk[38] apart has been documented previously. However, the mean results of the two tests were essentially identical.[38] The slight variability seen in four subjects fed the basal diet a second time, after having had two or three 30-day periods when they were fed dietary fiber, was not significant by the paired *t* test (Table 3). Thus, the results observed when the subjects consumed the fiber-supplemented diets probably do reflect the effects of these sources of dietary fiber. The reproducibility of the effects of dietary fiber on the oral glucose tolerance test was demonstrated in three subjects fed the same source of dietary fiber 2–3 months apart.

Additional evidence that dietary fiber affects carbohydrate metabolism comes from our findings that the 1 h postprandial serum glucose concentrations were lower in six subjects when they were fed fiber-supplemented diets (CB or SH) than when they were fed the basal diet. Two subjects, who had a symptomatic reactive hypoglycemia towards the end of the oral glucose tolerance test when fed the low-fiber diet, experienced no reactive hypoglycemia when fed the fiber (CB or SH)-supplemented diet (Figure 5). Similar observations were reported by Haber et al.[39]

These effects of some sources of dietary fiber on glucose metabolism may be useful in the dietary control of diabetes. Recently, Miranda and Horwitz[40] reported that diets containing 20 g of crude fiber significantly reduced the mean plasma glucose and the insulin requirements in eight insulin-taking diabetics. The amounts of dietary fiber sources fed in our study were within the practical range for daily consumption (26 g), and the vehicle used (bread) was fed in acceptable amounts (180 g per day).

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